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## Effects of temperature and strain rate on the forming limit curves of AA5086 sheet

Cunsheng Zhang<sup>a,b</sup>, Xingrong Chu<sup>c\*</sup>, Dominique Guines<sup>d</sup>, Lionel Leotoing<sup>d</sup>, Jie Ding<sup>a</sup>,  
Guoqun Zhao<sup>a</sup>

<sup>a</sup> School of Materials Science & Engineering, Shandong University, Jinan, Shandong 250061, P.R.China

<sup>b</sup> State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan 410082, P.R.China

<sup>c</sup> School of Mechanical, Electrical and Information Engineering, Shandong University at Weihai, Weihai 264209, P.R.China

<sup>d</sup> Université Européenne de Bretagne, France, INSA-LGCGM - EA 3913 20, avenue des Buttes de Coësmes 35043 RENNES Cédex

### Abstract

During the warming forming process of aluminum alloys, both temperature and strain rate have significant influences on sheet formability. However, current research regarding the effects of temperature and strain rate on the forming limit curves of aluminum alloys is still lacking. Due to the difficulty in carrying out the experiments for obtaining forming limit curves under dynamic forming conditions at elevated temperature, in this work, the method is proposed to investigate these effects by combining a modified Voce constitutive model (Lin-Voce model) with the numerical simulation of Marciniak test. On the basis of experimental data obtained by the tensile tests, the material parameters of Lin-Voce model are identified by the inverse analysis technique. Then, the proposed Lin-Voce model is verified by comparing numerical and experimental results obtained by Marciniak test. Finally, the numerical simulation of Marciniak test is carried out at different temperatures (100, 200 and 300 °C) and punch speeds (10, 750 and 1000 mm/s), and the effects of temperature and strain rate on the forming limit curves of AA5086 are investigated and discussed.

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**Keywords:** Strain rate; Forming limit curves; Marciniak test

\* Corresponding author. Tel.: +86 -6315688338; fax: +86 -6315688338  
E-mail address: [xrchu@sdu.edu.cn](mailto:xrchu@sdu.edu.cn)

## 1. Introduction

Due to its good characteristics of small density, high specific strength and good weldability, aluminum alloys have become the best lightweight materials. However, compared with conventional steels, the sheet formability of aluminum alloys at room temperature is relatively low, which greatly limits their application (Miller et al. 2000).

In order to improve the sheet formability of aluminium alloys, warm forming process has been developed and attracted more and more attention today. Recently, scholars have done much work on sheet warm formability by different experimental methods. The formability of AA7075 was studied by WANG et al. (2012) through the limiting drawing ratio test and the limiting dome height test. It was found that the sheet formability could be significantly improved when the blank was heated to 140-220 °C. Mahabunphachai and Koç (2010) found that the formability of AA5052 and AA6061 increased with temperature (from room temperature to 300 °C) and decreased with strain rate (0.0013 and 0.013 s<sup>-1</sup>) by bulge tests. Li and Ghosh (2004) investigated the formability of AA5754, AA5182 and AA6111-T4 by forming rectangular designed parts at the strain rate of 1s<sup>-1</sup> from 200 to 350 °C. It was shown that temperature had a significant positive effect on the sheet drawing formability and this effect varied for these three materials. Palumbo and Tricarico (2007) investigated the formability of AA5754-O through the warm deep drawing equipment, which could be improved obviously at a certain temperature. The study of Wang et al. (2011) also showed that both temperature and punch speed had a strong influence on the formability of AA2024 by the cup punch test. By performing cylindrical deep drawing tests, Naka and Yoshida (1999) found that the limiting drawing ratio of AA5083-O increased with the increasing die temperature and decreased with the increasing forming speed.

As an effective tool to evaluate the formability of sheet metals, forming limit curves, developed by Keeler and Backofen (1963) in the 1960s, is widely used now. It is known from the literatures above, aluminum alloy becomes very sensitive to strain rate at warm forming temperatures, and exhibits very different mechanical properties at high strain rates and quasi-static strain rates (Tarigopula et al., 2008). Naka et al. (2001) investigated experimentally the effects of forming speed and temperature on the forming limit curves of AA5083-O by performing stretch-forming tests at various forming speeds (0.2-200 mm/min) and temperatures (20-300 °C). It was shown that forming limit curves increased drastically with the decreasing speed for any strain path at high temperatures ranging from 150 to 300 °C, while at room temperature the forming limit curves was not sensitive to forming speed. Chu et al. (2014) obtained the forming limit curves of AA5086 under different temperatures (20,150 and 200 °C) and strain rates (0.02, 0.2 and 2 s<sup>-1</sup>) by Marciniak test and the M-K model. It was found that both temperature and strain rate have an important influence on the forming limit curves of AA5086.

Due to the complexity and difficulty in carrying out the physical Marciniak test under high forming speeds and at elevated temperatures, current studies regarding the effect of strain rate on forming limit curves are mostly based on Marciniak-Kuczynski theory, but only a small range of strain rate was covered in these works, so the research about the effects of strain rate and temperature on the forming limit curves of aluminum alloys is still relatively lacking. Therefore, the purpose of this work is to propose a modified Voce constitutive model (named Lin-Voce constitutive model) and to investigate the effects of temperature and strain rate on forming limit curves of AA5086 by combining the proposed constitutive model and Marciniak test. Material parameters in Lin-voce constitutive model are identified by the inverse analysis technique and verified by carrying out Marciniak test. Finally, by combining the identified model and the numerical simulation of Marciniak test, the effects of temperature (100, 200 and 300 °C) and punch speeds (10, 750 and 1000 mm/s) on forming limit curves of AA5086 are discussed.

## 2. Construction and identification of a modified constitutive model

### 2.1. Construction of a constitutive model

Voce hardening law is usually used to describe the rheological behaviour of the aluminium alloys which exhibit a saturation stress-strain state when a great equivalent strain arrives at high temperatures (Diot et al., 2006). In this work, a modified Voce constitutive model called Lin-Voce is proposed to describe the flow behaviour of AA5086, as shown in Eq.1.

$$\bar{\sigma} = \sigma_Y + (C_1 + C_2 T) \sqrt{1 - \exp(-C_3 \bar{\epsilon})} \bar{\epsilon}^{\frac{1}{C_4} \exp(C_5 T)}, \quad (1)$$

where  $\bar{\sigma}$  is the flow stress,  $\sigma_Y$  is the yield stress,  $C_1$  and  $C_2$  are the strain hardening coefficients,  $C_3$  is the strain softening coefficient,  $C_4$  and  $C_5$  are strain rate sensitivity coefficients.

## 2.2. Material parameters identification based on the inverse analysis technique

Due to the irregular cross-section of the specimen, it is difficult to obtain the material parameters in Lin-Voce model. Hence, the inverse analysis technique is used in this work. The basic concept of an inverse analysis for parameter identification is to find out a set of unknown material parameters by continuous iterations based on numerical simulation and experimental data. Here, the hypothesis that the yield strength depends only on temperature but not on strain rate is adopted, which is commonly verified for aluminium alloys (Pedersen et al., 2008). Thus, in this paper, the yield strength is set as a variable and identified by the inverse analysis, as listed in Table 1.

Experimental data used in the inverse analysis technique is provided by the previous dynamic tensile tests in the literature (Zhang et al., 2010), which have been carried out under different temperatures (20, 230 and 290 °C) and different forming rates (10, 750 and 1000 mm/s).

Fig. 1 illustrates experimental and identified force-time curves at different forming conditions. From the figure, the identified curves have an excellent agreement with experimental ones at 10mm/s. Considering the measurement errors caused by the vibrations of the testing system at high tensile speeds, the little discrepancy between fitted and experimental curves is acceptable. The maximum error between experimental and fitted curves is only 2.656%, as listed in Table 2. It can be concluded that Lin-Voce constitutive model is suitable to describe the deformation behaviour of AA5086 under the dynamic tensile conditions.

Table 1. Yield strength of AA5086 identified at different temperatures.

Temperature /°C	Yield strength /MPa
20	134.81
230	133.43
290	125.51

Table 2. Identified parameters in Lin-Voce constitutive model by the inverse analysis technique.

Tensile speed	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	Error
10mm/s	756.26	-1.0387	1.5508	0.00974	0.00003868	1.86%
750mm/s	726.88	-0.8693	1.2932	0.00317	0.00003166	2.66%
1000mm/s	698.83	-0.8392	1.5714	0.01038	0.00002545	2.48%

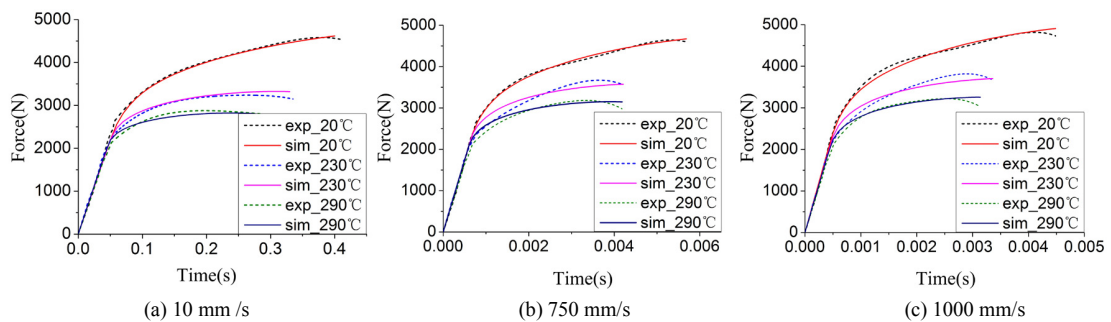


Fig. 1. Comparison of experimental force-time curves and ones fitted with Lin-Voce model.

### 2.3. Verification by Marciniak test

#### 2.3.1. Preparation and results analysis of Marciniak test

To verify the proposed constitutive model, a Marciniak test setup is designed, and its schematic illustration is shown in Fig. 2. To facilitate capturing the deformation process of the blank, a reverse structure with a bell jar is designed. An optical mirror is used to reflect the forming process to the high speed camera. Limit strains of every specimen are calculated by digital image correlation technology.

Different strain paths, ranging from uniaxial tension through plane strain to equi-biaxial stretching, can be covered by 13 specimens with different widths (Fig. 3). To assure the occurrence of the maximal strains (to trigger localization) on the centre part of the blank and eliminate the effect of friction on forming limits, the specimens are designed with non-uniform thicknesses. The central part has a thickness of 0.8 mm, while the adjacent and the clamping parts are in 1.5 and 2.0 mm, respectively. The specimens are sprayed with paints to produce a random distribution of speckle pattern. Finally, the Marciniak test is carried out under a punch speed of 10mm/s at room temperature. To predict the occurrence of necking, a failure criterion widely used for the Marciniak-Kuczynski model is adopted: when the ratio of average equivalent plastic strain increments in the localized and non-localized zone reaches 7, localized necking is assumed to occur. At this moment, the principal strains in the localized zone are retained as limit strains.

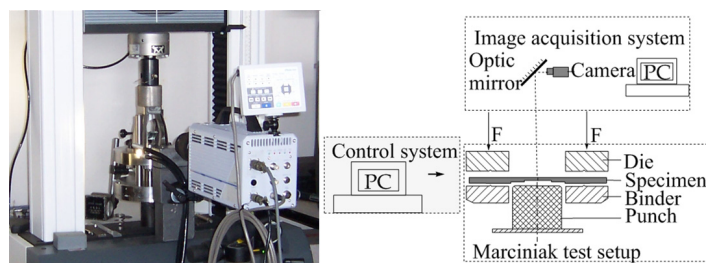


Fig. 2. Marciniak test setup and its schematic illustration.

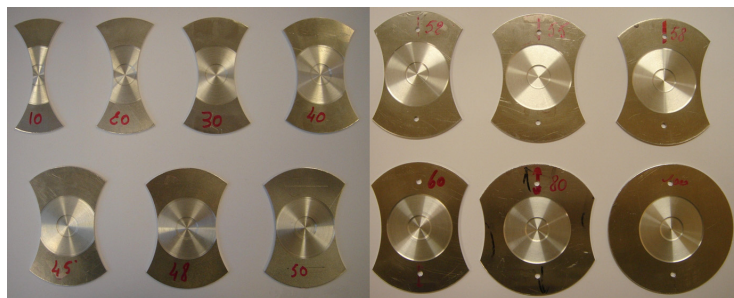


Fig. 3. Specimens used in Marciniak test.

#### 4.2.2. Construction of the FE-Marciniak model

Corresponding to the experimental setup in Fig. 2, the FE-Marciniak model consists in three parts: a rigid cylindrical punch with a flat bottom, a rigid die and a deformable specimen. Due to the symmetrical boundary conditions, only a quarter part of the geometrical model is considered, as shown in Fig. 4. The die remains fixed during the simulation process and the blank-holder is simulated by a pressure load directly applied on the specimen. The pressure load is set to an enough large value of 100 kN to prevent sliding between the blank and the die or the blank-holder. As the thickness of specimen is non-uniform, the centre of the blank and the punch is non-contact in the experimental Marciniak test. Therefore, the friction coefficient of Coulomb's law between blank and punch in the FE-Marciniak model is set to 0, while it is set to 0.05 and 0.1 between the blank and the parts with thickness of 1.5 mm and 2.0 mm, respectively. Lin-Voce constitutive model is implemented into the FE-Marciniak model via ABAQUS UHARD subroutine.

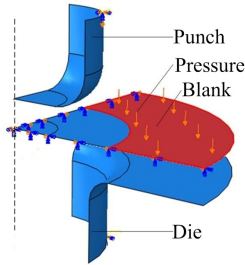


Fig. 4. Illustration of FE-Marciniak model.

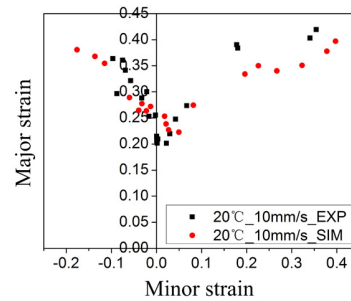


Fig. 5. Comparison of forming limit curves obtained by the physical Marciniak test and FE-Marciniak model.

Fig. 5 shows the forming limit curves obtained by the physical Marciniak test and FE-Marciniak model at the punch speed of 10 mm/s at room temperature. A great consistency can be observed, which also proves that Lin-Voce constitutive model is suitable for describing the deformation behaviour of AA5086 under different strain conditions.

### 3. Prediction of the effects of the temperature and strain rate on the forming limit curves of AA5086

In this section, with the identified Lin-Voce constitutive model, the numerical simulation of Marciniak test is carried out at different temperatures (100, 200 and 300 °C) and punch speeds (10, 750 and 1000 mm/s). Fig. 6 and Fig. 7 show the obtained critical points and fitted forming limit curves of AA5086 for different temperatures and punch speeds.

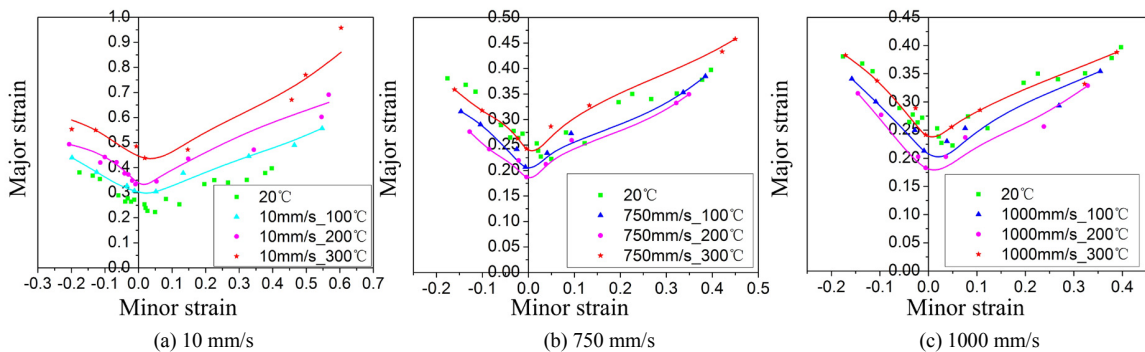


Fig. 6. Comparison of forming limit curves for different temperatures at given punch speed.

It can be observed from Fig. 6 that forming temperature has a significant influence on forming limit curves of AA5086. The limit strain increases with the rising temperature at 10 mm/s. Compared to those at room temperature, the limit strains under the uniaxial tension, the plane strain and the equi-biaxial stretching are increased by 51.3%, 92.9% and 116.59%, respectively. However, under dynamic forming conditions (750 and 1000 mm/s), the negative effect of strain rate plays a prominent role, which offsets the positive effect of temperature on sheet formability, resulting that the forming limit curve at 200 °C is lower than that at room temperature. While with the increasing temperature, the positive effect of temperature on the sheet formability gradually compensates the negative effect of strain rate, consequently, the forming limit curve at 300 °C is close to that at room temperature.

Considering that the relatively little difference in strain rate at 750 mm/s and 1000 mm/s, only the forming limit curves at 10 and 1000 mm/s are compared to discuss the effect of strain rate on forming limit curves. Fig. 7 shows that forming limit curves at high punch speed is always lower than that at low punch speed at a given temperature, indicating that strain rate has a negative effect on sheet formability. For example, at 200 °C, the limit strains at 1000 mm/s under the uniaxial tension, the plane strain and the equi-biaxial stretching are decreased by 36.1%, 45.2% and 50.2% compared to that at room temperature.



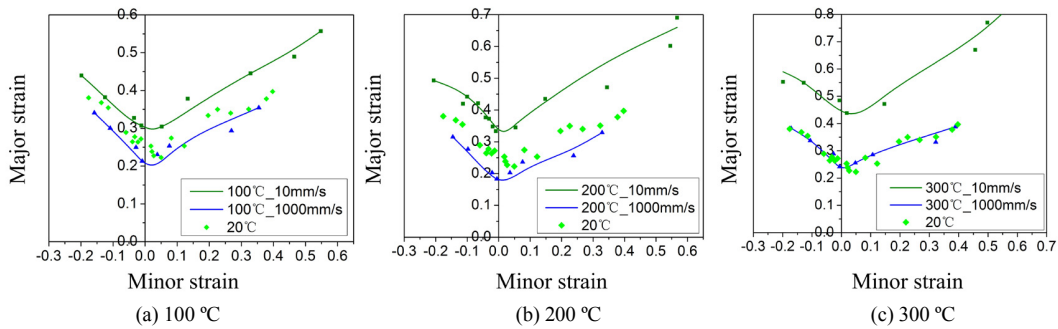


Fig. 7. Comparison of forming limit curves under different punch speeds at a given temperature.

Thus, for aluminium alloys, the warm formability depends on the offsetting interaction of temperature and strain rate. Under low forming speed (10 mm/s), temperature plays a prominent role due to the low strain rate. The positive effect of temperature on the sheet formability is dominant, as a result, the sheet formability is improved. On the contrary, at dynamic forming conditions, the negative effect of strain rate plays a prominent role on sheet formability, and leads to the decrease of the sheet formability. This is why the formability at 200 °C becomes lower than that at room temperature. As the temperature increases, the positive effect of temperature is enhanced and compensates the negative effect of strain rate. When temperature reaches 300 °C, there is a balance between the effects of temperature and strain rate, consequently, the sheet formability at this temperature is close to that at room temperature.

#### 4. Conclusions

In this work, the method is proposed to investigate the temperature and strain rate effects on AA5086 formability by combining a modified Voce constitutive model with the numerical simulation of Marciniak test. The following conclusions are drawn:

The proposed Lin-Voce constitutive model is suitable for describing the rheological behaviour of AA5086 under different strain conditions.

Forming temperature has a positive effect on forming limit curves of AA5086. The limit strain increases with the rising temperature at 10 mm/s. However, under dynamic forming conditions (750 and 1000 mm/s), the negative effect of strain rate offsets the positive effect of temperature on sheet formability, resulting that the forming limit curve at 200 °C is lower than that at room temperature. Due to the interaction of temperature and strain rate, under dynamic condition, the forming limit curve at 300 °C is close to that at room temperature.

The formability at high punch speed is always lower than that at low punch speed at a given temperature, indicating that strain rate has a negative effect on sheet formability.

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